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**Multi-Method Paleoseismology: Characterizing the Activity of the West Tahoe Fault
On and Offshore: Collaborative Research with UCSD and SDSU**

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Abstract

In the summer of 2006, investigators from Scripps Institution of Oceanography, San Diego State University and the University of Nevada, Reno conducted a multi-method paleoseismic investigation of the West Tahoe fault, with particular focus on the southern extent of the largest bounding fault in the Tahoe basin. Over a two week period, the West Tahoe fault was mapped using subbottom CHIRP sonar in both Fallen Leaf Lake and Lake Tahoe, providing evidence for both fault continuity and history of recent slip (i.e., MRE). High-resolution seismic profiles with sub-meter resolution, integrated with more conventional on-land fault mapping, were used to confirm previously mapped fault scarps south of Lake Tahoe and confirm a total fault length of at least 50 km for this down-to-the-east normal fault. Piston- and gravity-cores were also collected in Fallen Leaf Lake (Dr. Bob Karlin and graduate student Shane Smith, UNR) to establish a chronostratigraphy for the shallow most sediments (~ 5 m); preliminary C-14 dates indicate sedimentation rates of approximately 1 m/ka in the southern end of Fallen Leaf Lake. The most recent rupture along the southern segment of the West Tahoe fault is overlain by approximately 4-5 m of sediment as seen within CHIRP profiles within Fallen Leaf Lake, indicating a tentative MRE of 4-5 ka. C-14 dating of a submerged tree on the hanging wall of the West Tahoe fault near Baldwin Beach (Lake Tahoe) was analyzed as part of this project with an inundation date of 4.6 ka; although the occurrence of this tree in 4-m-water-depth was previously published to result from a period of aridity in the mid-Holocene (Lindstrom, 1990), it may indeed be tectonic in origin and date the MRE event along the West Tahoe fault. CHIRP profiles were also collected in Lake Tahoe, including a several profiles crossing the West Tahoe fault near Rubicon Bay and show several meters of sediment overlying the latest rupture of a nearby synthetic fault to the West Tahoe fault. This event may correspond to the MRE seen in Fallen Leaf Lake CHIRP profiles, although a future core and C-14 analysis near Rubicon Bay will be needed to fine-tune sedimentation rates near this most recent rupture to confirm synchronicity (if any). As part of this proposal, we were also tasked with finding sites suitable for on-land paleoseismic trench study; to this end, potential sites were identified south of HWY 89 near Baldwin Beach, Angora Ridge near Angora Lakes parking lot, and due north of Osgood Swamp near Meyers, California. Incidentally, the recent Angora Ridge firestorm near South Lake Tahoe burned across the fault scarp, through a heavily forested area, between Osgood Swamp and Angora Lakes Parking lot, providing additional opportunities for mapping in a region that was previously too heavily forested to reliably follow the fault trace.

Introduction

Offshore paleoseismic studies in the Lake Tahoe Basin (LTB) have defined the regional distribution of faults, slip rates, and combined with onshore excavations, have led to estimates of paleoearthquake timing and magnitude (Dingler et al., submitted; Seitz et al., in prep). By combining data from sediment cores and CHIRP profiles, we can capture the rupture history and provide constraints on the regional-scale deformation. The most active, but poorly understood structure in the LTB is the N-S striking West Tahoe Fault (WTF) (Fig. 1). Dingler et al. (2007) and Kent et al. (2005) estimate the vertical slip-rate along the WTF based on offset paleoshoreline features in Lake Tahoe, but did not investigate timing and magnitude of the most recent event (MRE). Here we present preliminary results from a comprehensive geophysical survey, including detailed sub-bottom mapping, sediment coring and onshore reconnaissance conducted along the southern segment of the WTF between Emerald Bay and Echo Lake. Our results, combined with previous work on segments to the north of Emerald Bay (Dingler et al., 2007) suggest the WTF may be the most active and potentially the most hazardous structure in the LTB, considering the average recurrence interval and the MRE date; the West Tahoe fault may well represent the greatest conditional probability for rupture—even exceeding that of the Genoa fault. Constraining the likelihood for future large-magnitude events along the West Tahoe fault is vital for hazard assessment in the heavily populated Lake Tahoe-Carson City-Reno corridor.

Quaternary Geology and Tectonics of Tahoe Basin

The Lake Tahoe Basin lies on the boundary between two distinctly different tectonic provinces, the relatively stable Sierra Nevada–Great Valley (SNGV) block to the west (Argus and Gordon, 2001) and the deforming Walker Lane belt (WLB) to the east (Svarc et al., 2002). This boundary is a kinematically separate

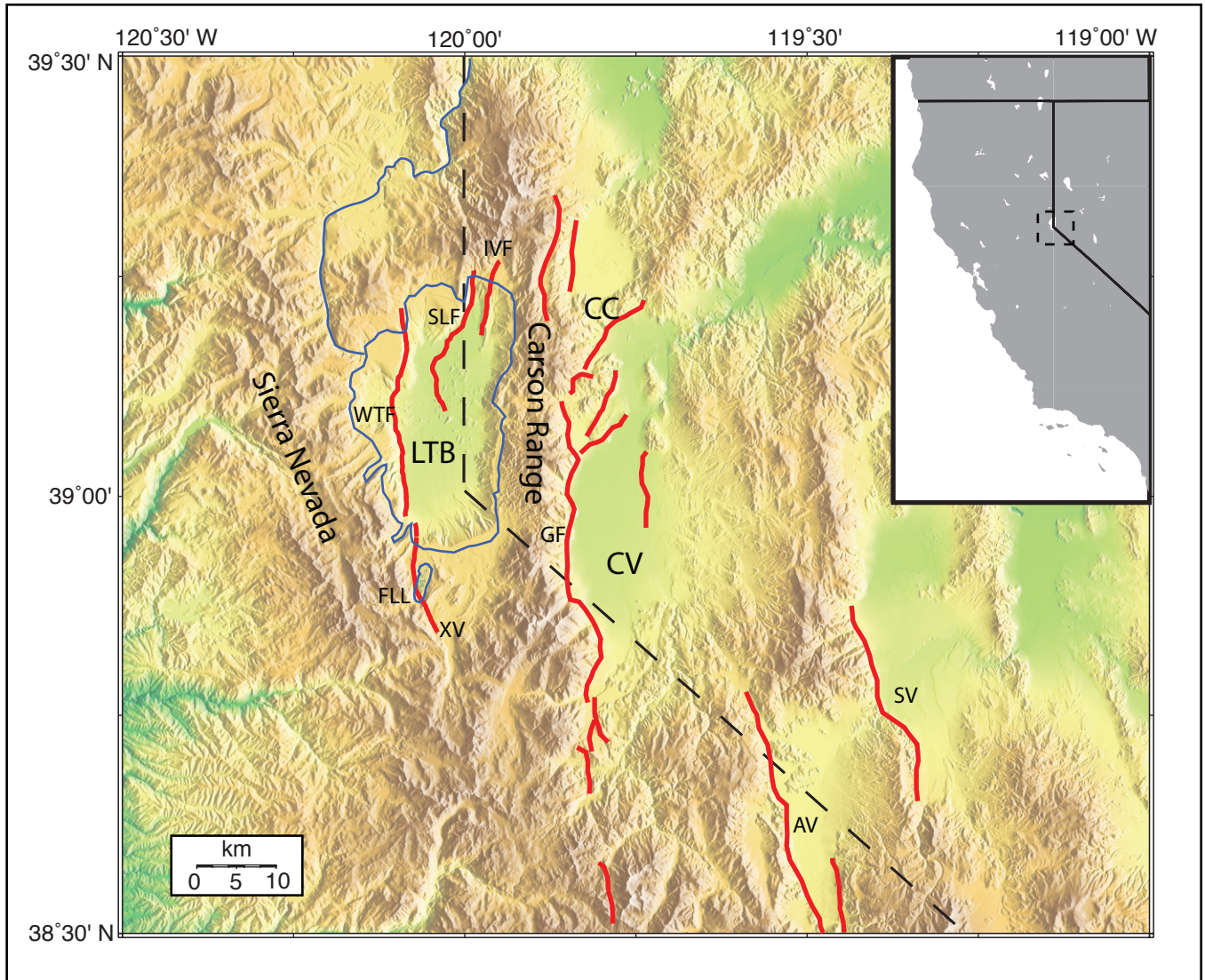


Figure 1. Generalized fault and topographic map of eastern California and western Nevada. Red lines are active fault systems. Fault abbreviations: WTF, West Tahoe Fault; SLF, Stateline Fault; IVF, Incline Village Fault. Other abbreviations: LTB, Lake Tahoe Basin; FLL, Fallen Leaf Lake; XV, Christmas Valley; CC, Carson City; CV, Carson Valley; AV, Antelope Valley; SV, Smith Valley.

domain from the Basin and Range Province to the east (Stewart, 1988). Approximately 12 mm/yr of northwest dextral shear (~25% of the total Pacific-North American plate motion) plate motion is transferred from the San Andreas System northward through the Eastern California Shear Zone and into the WLB (Bennett, 2003; Dixon et al., 2000; Dokka, 1990; Miller et al., 2001). The strain is partitioned across several strike-slip and normal faults as a response to the oblique-divergent relative motion between the Sierra Nevada microplate and stable North America (Cashman et al., 2000; Unruh et al., 2003), with the eastern margin of the Sierra Nevada Range defined by a series of left-stepping, range bounding normal faults (Wakabayashi and Sawyer, 2001). South of Lake Tahoe (~lat 38.5°N), the Sierra Nevada frontal fault system splits into two extensional domains separated by the Carson Range (Figure 1): the Lake Tahoe Basin and the Carson Valley, both characterized by active down-to-the-east normal faults. The branching of the Sierra Nevada frontal fault system has been interpreted as a response to a discrete right (releasing) step along the boundary of the Sierra Nevada microplate (Unruh et al., 2003).

Regional geodetic data indicates the WLB accommodates significantly more extensional strain than the Basin and Range province (Bennett, 2003; Dixon et al., 2000; Hammond, 2004; Svarc et al., 2002; Thatcher et al., 1999). Studies using geological and thermochronological data indicate a younger period of extension moving westward from the eastern Basin and Range province into the WLB, with uplift of the eastern Sierra Nevada

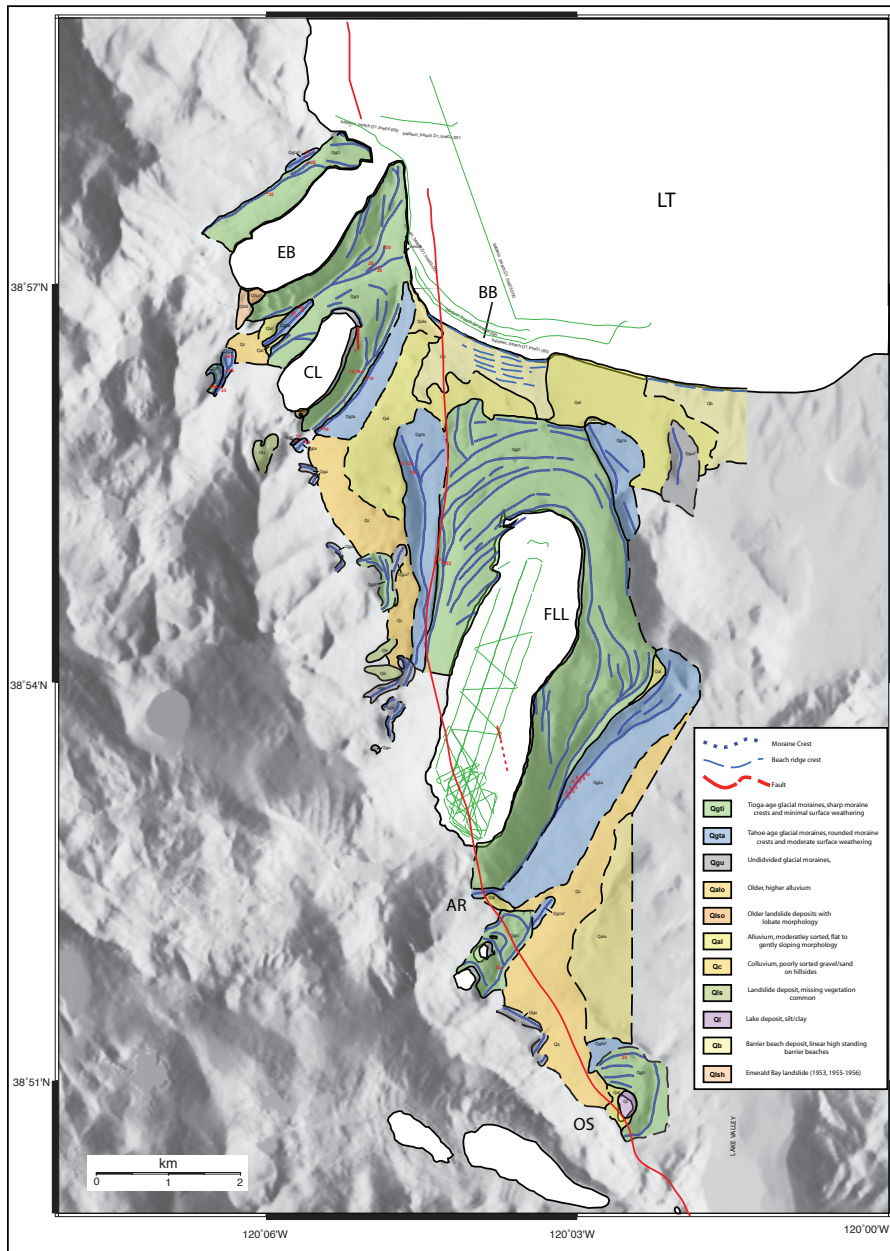


Figure 2. Topographic basemap including glacial stratigraphy of McCarthy (2003) is highlighted near Fallen Leaf Lake. Tioga deposits are shown in green, while older Tahoe deposits are blue. Inferred location of the West Tahoe Fault (red) and seismic CHIRP profiles (green) are also indicated.

mm/yr (Dingler et al., 2007). In addition to offshore imaging, an excavation across the Incline Village Fault, on the property of Incline Village Elementary School, revealed two and possibly three Holocene/late Pleistocene ruptures that are M7 or greater (Seitz et al., in prep).

Within the Lake Tahoe Basin four identifiable glaciations have overprinted the landscape and drastically altered lake-level (Birkeland, 1964). The most recent Tioga glaciation began ~24,500 yr B.P. and ended by ~13,600 yr B.P. (Benson et al., 1998; Phillips et al., 1996). The glacier responsible for creating the elongate valley containing Fallen Leaf Lake was larger than adjacent valley glaciers through Cascade Lake and Emerald Bay. The Fallen Leaf glacier was sourced from a large icecap in Desolation Valley, along with smaller tributary glaciers originating from nearby cirques. The landscape surrounding Fallen Leaf Lake is almost entirely glacially derived, with large ~300 m high lateral moraines extending over 5 km from the mouth of the Sierran range front toward Lake Tahoe, as well as hummocky topography associated with smaller Tioga recessional moraines from

beginning ~5 Ma (Wakabayashi and Sawyer, 2001) and depression of the LTB beginning between 10 Ma and 3 Ma (Surpless et al., 2002). Apatite fission track thermochronology (Surpless et al., 2002) and the concentration of contemporary deformation along normal and right-lateral faults along the western edge of the Sierra Nevada (Bennett, 2003; Dixon et al., 2000; Hammond, 2004; Svarc et al., 2002; Thatcher et al., 1999) supports the notion that Basin and Range extension has been encroaching westward from central Nevada into the easternmost Sierra Nevada block.

The LTB is characterized by down-to-the-east, north-south-striking normal faults in response to east-west oriented regional extension. Savage et al. (1995) estimate that several mm/yr of northwest displacement may be occurring in the region between Carson City and the western side of the LTB. The active fault systems in this region, from west to east, are the West Tahoe-Dollar Point, Stateline-North Tahoe, Incline Village, and Genoa (Fig. 1). Active faults and slip rate estimates in the LTB were identified by Kent et al. (2005) and refined by Dingler et al. (2007) using a combination of seismic CHIRP and sediment core data. A 19.2 ± 1.8 ka wave-cut paleo-terrace (Kent et al., 2005), which correlates temporally with a 19 ± 1 ka glacial advance during the Tioga glaciation (Phillips et al., 1996), was used to calculate an extension rate across LTB of 0.53 – 1.15

just south of Lake Tahoe and beneath Fallen Leaf Lake (Figure 2). A UNR master's thesis (McCarthy, 2003) was focused on the chronology and geomorphology associated with Tahoe and Tioga high-stands in the region surrounding Fallen Leaf Lake. Using weathering and topographic nature to establish relative ages for moraines, McCarthy (2003) assigned most glacial deposits within the Fallen Leaf valley to Tioga age (~22-13 ka). Glacial and fluvial reworking and dense vegetation throughout LTB makes identification of fault scarps difficult both in the field and on aerial photos.

West Tahoe Fault

The WTF is the range bounding, east dipping normal fault along the western margin of the basin, and is largely located along the base of the western slope of Lake Tahoe. In the lake, the fault has clearly defined scarps that offset submarine fans, lake bottom sediments, and the McKinney Bay slide deposits (Hyne et al, 1972; Gardner et al, 2000; Kent et al, 2005; Dingler et al. 2007). The WTF can be separated into three primary segments that appear to be geomorphically distinct. Prior to this study, the WTF had not been positively identified outside of Lake Tahoe, and in particular, very little was known about the southern segment, herein referred to as the Fallen Leaf segment. The Fallen Leaf segment extends from Christmas Valley, north through Fallen Leaf Lake and offshore into Lake Tahoe, west of Baldwin Beach, but east of Emerald Bay. The WTF then appears to make a ~ 1 km westward step from the mouth of Emerald Bay to the base of the west shore slope then continues northward to McKinney Bay, completing the central segment. Along the McKinney Bay slide, any scarps appear to have been overprinted by active fan systems, but is easily identified at the northern edge of the slide and continues northward along the eastern edge of the Tahoe City shelf and eventually onshore in the vicinity of Kings Beach, California.

In addition to vertically offset paleo-terraces separated by the WTF on opposing sides of the lake (Kent et al., 2005), Dingler et al. (2007) presented several CHIRP profiles of the central and northern (aka Dollar Point fault) segments of the WTF along the lake floor. Several meter-high scarps along a fan-delta offshore of Sugar Pine Point (13-14 m high fault scarp), and sediments at the base of the shelf, offshore Rubicon, displaying up to 2 m of vertical offset are evidence for Holocene/Pleistocene activity. In addition, a cross-lake profile shows an ~0.1° dip and increasing sediment thickness towards the fault along the hanging wall block, indicative of regional tilting due to normal faulting (Dingler et al., 2007).

To better understand the nature of the Fallen Leaf Segment of the WTF, we conducted a geophysical survey in Fallen Leaf Lake and in Lake Tahoe, as well as onshore field mapping during July 2006. Using equipment from the Scripps Institution of Oceanography, sub-bottom seismic CHIRP profiles successfully imaged the WTF and identified offset sedimentary horizons. Onshore field mapping between Baldwin Beach and Christmas Valley identified scarps along the Fallen Leaf lateral

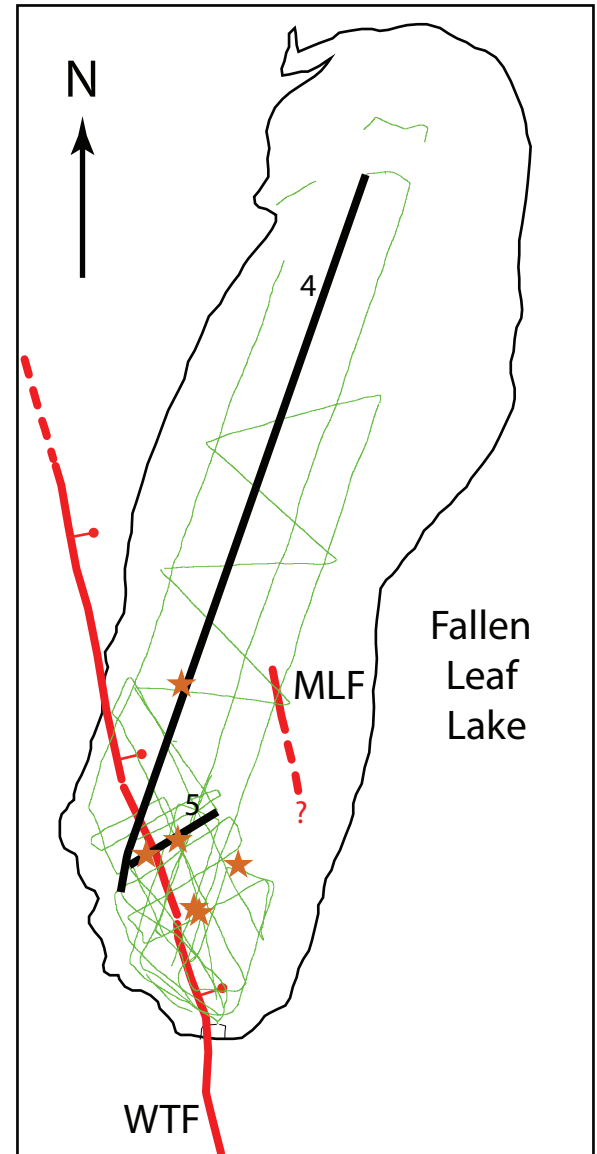


Figure 3. CHIRP survey profiles and sediment core locations in Fallen Leaf Lake. Green lines represent all CHIRP profiles, black lines are profiles discussed in this report, orange stars are sediment core locations, and red lines are faults. Abbreviations: WTF, West Tahoe Fault; MLF, Mid-Lake Fault. Several profiles cross the WTF in the southern part of the lake and two profiles imaged a second fault, the MLF, approximately 1 km east of the WTF.

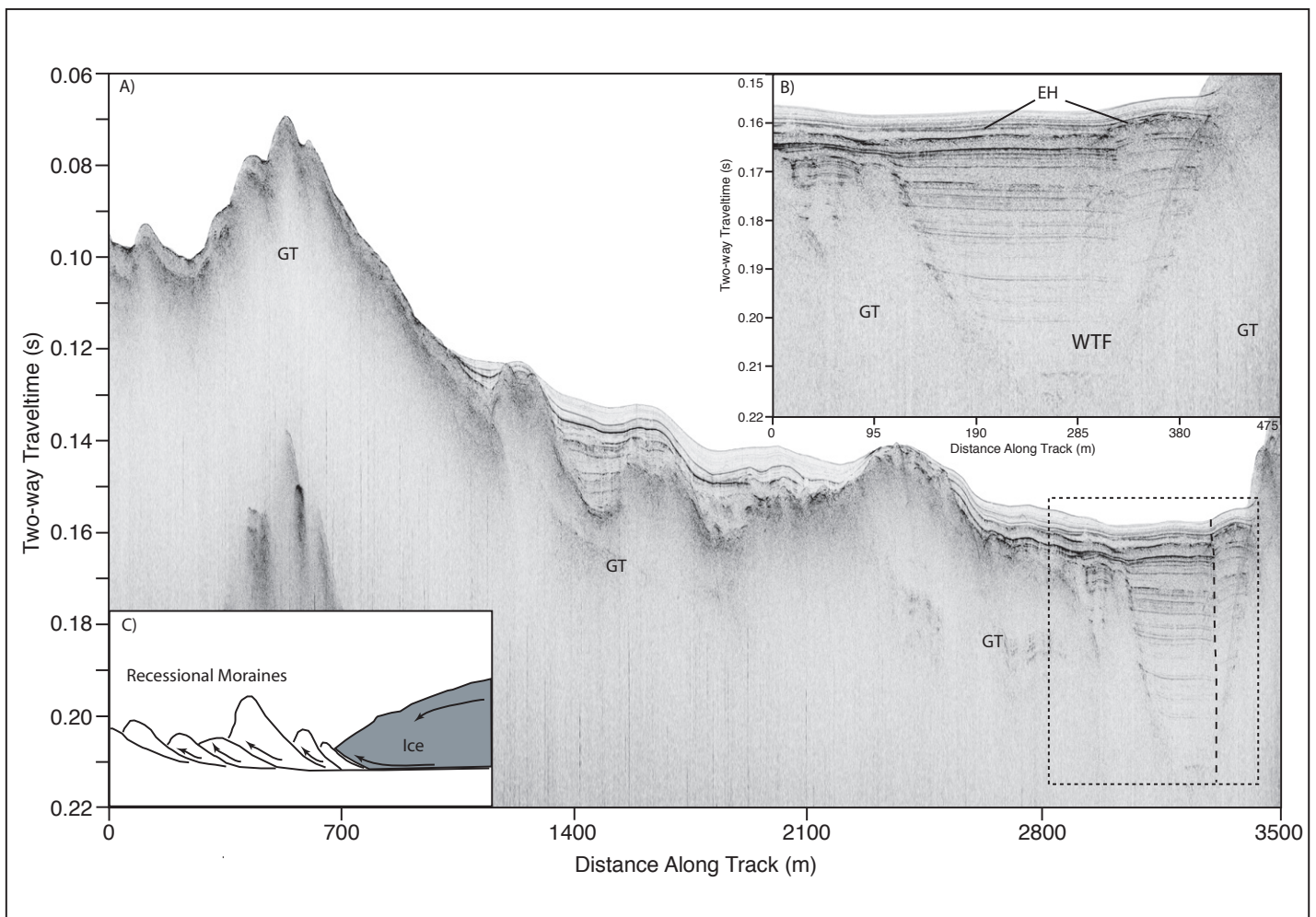


Figure 4. (A) Northeast trending profile spanning over 2/3' rds of FLL. The WTF is imaged in the southern end of the profile adjacent to a fault parallel slope. The WTF offsets lacustrine sediments that fill a ~50 m deep basin. (B) Blowup of the WTF zone in which sediments have been vertically offset by ~ 3 m. The most recent event (MRE) horizon (EH) can be correlated throughout the southern basin. (C) Hummocky topography along the glacial till (GT) is typical for moraines formed at glacier fronts by temporary stillstands or readvancements during overall retreat from its terminal moraine position. The hummocks are likely the same features as the arc-shaped ridges just north of the FLL in shown in Figure 2.

moraines with trends consistent with those determined from CHIRP crossings in Fallen Leaf Lake, and a several km-long section of the WTF south of HWY50. During October 2006, five piston cores and a single gravity core were collected in Fallen Leaf Lake using equipment from University of Nevada Reno. Radiocarbon analysis of samples from three of the piston cores were used for define ages of sedimentary horizons and estimate the timing of the most recent event (MRE) along the southern segment of the WTF; preliminary age dates suggest a sedimentation rate of 1m/ka, suggesting the timing of the MRE along the Fallen Leaf segment of the WTF in the 4-5 ka range.

Results: WTF Fallen Leaf Segment

Fallen Leaf Lake

Fallen Leaf Lake is ~5km long and ~1km wide with its long axis parallel to the trend of the valley. A high-density grid of seismic CHIRP profiles (Fig. 3) were collected in the southern portion of the lake, and a lower density grid continued northward allowing three-dimensional, basin-wide correlation between sedimentary horizons. Flat lying lacustrine deposits infill a series of basins, separated by what appear to be recessional moraines trending perpendicular, and lateral moraines trending parallel to the trend of the lake. A deep (> 50 m sedimentary thickness) basin abuts the slope southern part of the lake then shallows toward the north (Figure 4 & 5). The basin

is filled with horizontally layered lacustrine sediments that are occasionally disrupted by slide deposits coming down the basin walls. The southernmost basin is located approximately 500 m north of the Fallen Leaf Marina and nearest Glen Alpine Creek, one of the only significant post-glacial sediment sources to FLL. Stratigraphy in the upper 5 m can be correlated between CHIRP profiles throughout most of the lake, with some layers pinching out further from their source. CHIRP profiles image massive, poorly sorted moraine material that acts as sedimentary bedrock underlying the lacustrine deposits (Figure 4).

It appears the FLL bathymetry has formed through a combination of glacial and tectonic forces. The southern sedimentary basin is bounded by a steep ~100 m high slope that is subparallel to the long axis of the valley and glacial flow direction, but the base of the slope is also coincident with the WTF imaged along the lake floor. Based on the vertical magnitude of the slope and the glacial history at FLL, it appears that the fault has facilitated glacial erosion along the valley floor in a way similar to the development of a roche moutonnée. Any preglacial structure in the bedrock or an increased fracture density due to faulting may create a zone of preferential quarrying along the hanging wall block (lee side of glacial flow). Assuming the valley floor is entirely reworked through each glacial maximum, with Tioga being the most recent, it is very unlikely that an ~100 m high scarp has formed during the last ~13 ka from tectonic events. Long-axis topographic profiles over Fallen Leaf Lake and Emerald Bay, extending from the range front to the Lake Tahoe shoreline, are drastically different. Other glacial features in FLL were imaged in CHIRP profiles, including a series of small (100 m wide) glacial basins along the

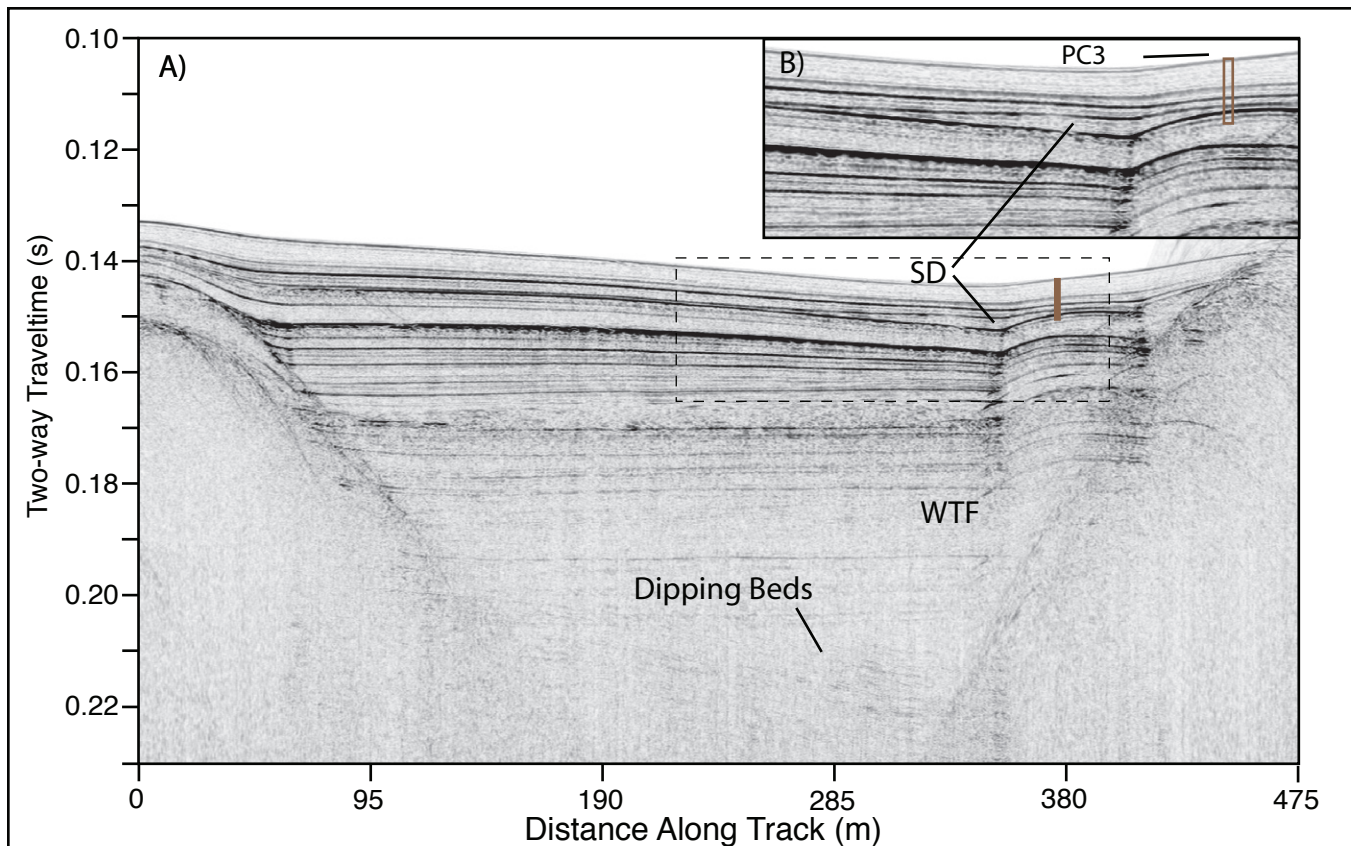


Figure 5. (A) Northeast oriented, fault-perpendicular profile (see Figure 3). Slip during the most recent event (MRE) was up to ~3 m in the upper 30 m of sediments. The increase in offset with depth is likely due to changes in sediment compaction rather than multiple events. A slide deposit (SD) mantles the event horizon and infills the accommodation created during the MRE. Piston core 3 sampled a sandy turbidite layer that is interpreted to be the distal reaches of the same slide sampled in piston core 1. Radiocarbon dating and the presence of the 7,600-8,000 year old Tsoyowata Ash place the MRE at ~4,000-5000 years B.P. and constrain the sedimentation rate at ~1 mm/yr over the last ~8 ka. Down-section, faintly imaged strata along the hanging wall abruptly change from horizontal to a ~4° dip towards the fault. The change in dip is interpreted to have formed during older events along the WTF. B) Enlarged section showing deformation associated with the MRE and the projected location of PC3 onto the profile (the two are offset by < 30 m).

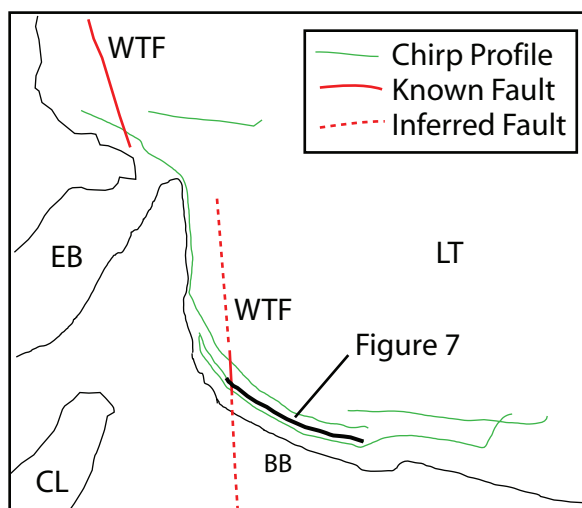


Figure 6. CHIRP profiles collected offshore Baldwin Beach (green) and location of the West Tahoe fault (red).

The apparent growth in down section offset is most likely due to the ductile nature of sediments in the upper 5 m, producing a fault propagation monocline above the fault tip. Diffraction hyperbole produced at stratigraphic terminations give the appearance of folding at depth, when in reality the horizons have been vertically offset by over 3 m. The total vertical offset that occurred during the MRE is ~3 m. Approximately 30 m below the lake floor, the stratigraphy abruptly changes in character with a marked increase in dip of about 4° toward the fault. Although the change in dip down section is most likely related to the pen- and tri-ultimate events on this section of the WTF, it is difficult to resolve the actual thickness of the wedge and the amount of coseismic offset (6 m of total Holocene offset preceding the MRE).

To constrain sedimentation rates and timing of the MRE, five piston cores and one gravity core were collected in the southern half of FLL. Representative lithology and magnetic susceptibility logs versus depth were generated for all cores. Each of the piston cores sampled over 4 m and all except one can be easily correlated based on color, texture, lithology and character of the susceptibility oscillations. Comparing core logs to acoustic logs derived from CHIRP data provides lithological constraints on the seismic stratigraphy imaged in FLL. In addition, chronostratigraphic control on cores and seismic images was achieved in two ways: first, by extracting radiocarbon samples from the cores and analyzing them with an accelerator mass spectrometer (AMS) and second, presence of Tsoyowata Ash layer in PC5 has provided a separate, but reliable constraint. Increases in magnetic susceptibility likely reflect increased concentrations of ferrimagnetic material derived from terrigenous sources. High susceptibility may indicate either significant run-off and clast input from the basin margins or from Glen Alpine Creek, where igneous source rocks have a high magnetic susceptibility.

The most important marker bed in the southern basin is a turbidite deposit that is associated with a slide off the southeastern shoreline. The slide deposit is imaged in CHIRP profiles as a distinct chaotic and convoluted layer that has disrupted the underlying stratigraphy in the proximal region, then grades into a thin, transparent layer mantling the strata below in the distal region. The chaotic portion of the deposit is imaged up to 200 m away from the slope break in the southern basin and the mantled deposit is seen essentially throughout the entire southern basin, ranging in thickness from ~0.4 m to ~1.5 m. The extensive run-out (>1,000 m) away from the slide source indicates the slide occurred very suddenly and had high velocity.

The wedge that has infilled the accommodation created during the MRE along the WTF (Figure 5) is in fact the distal slide deposit draped over the event horizon. Though it is difficult to distinguish between coseismic and postseismic triggering, it appears the turbidite slide is coincident with the last major event on the WTF. Radiocarbon analysis of a pine needle at the bottom of the PC3 place the sedimentation rates at ~1mm/yr over the last 4,800 years. Therefore the MRE occurred ~4-5 ka. In addition, the 7,600-8,000 year old Tsoyowata Ash was sampled at a depth of ~3 m, between two sand layers. The nearest CHIRP profile shows a dark

northern half of the lake, which are primarily filled with lacustrine sediments, but also show evidence for landslide and turbidite deposits. Based on the hummocky topography of the glacial substratum, it appears the northern half of the lake records fluctuating terminal moraines (Figure 4).

CHIRP profiles clearly image the WTF in the southern part of the lake, where it trends ~N20°W. The imaged fault projects into both fault scarps mapped along the eastern and western lateral moraine crests (Figure 5), thus confirming the location of earlier reconnaissance-level onshore fault. In the upper 30 m of sediments, the MRE horizon is defined by an upward terminating fault propagation fold overlain by a divergent wedge that infills accommodation space created during the MRE (Figure 5, inset). The offset is down-to-the-east and increases with depth, with the on-fault event horizon at 4.75 m below the lake floor (assuming 1500 m/s sound velocity), then shallowing on the footwall block to within 3.7 m of the

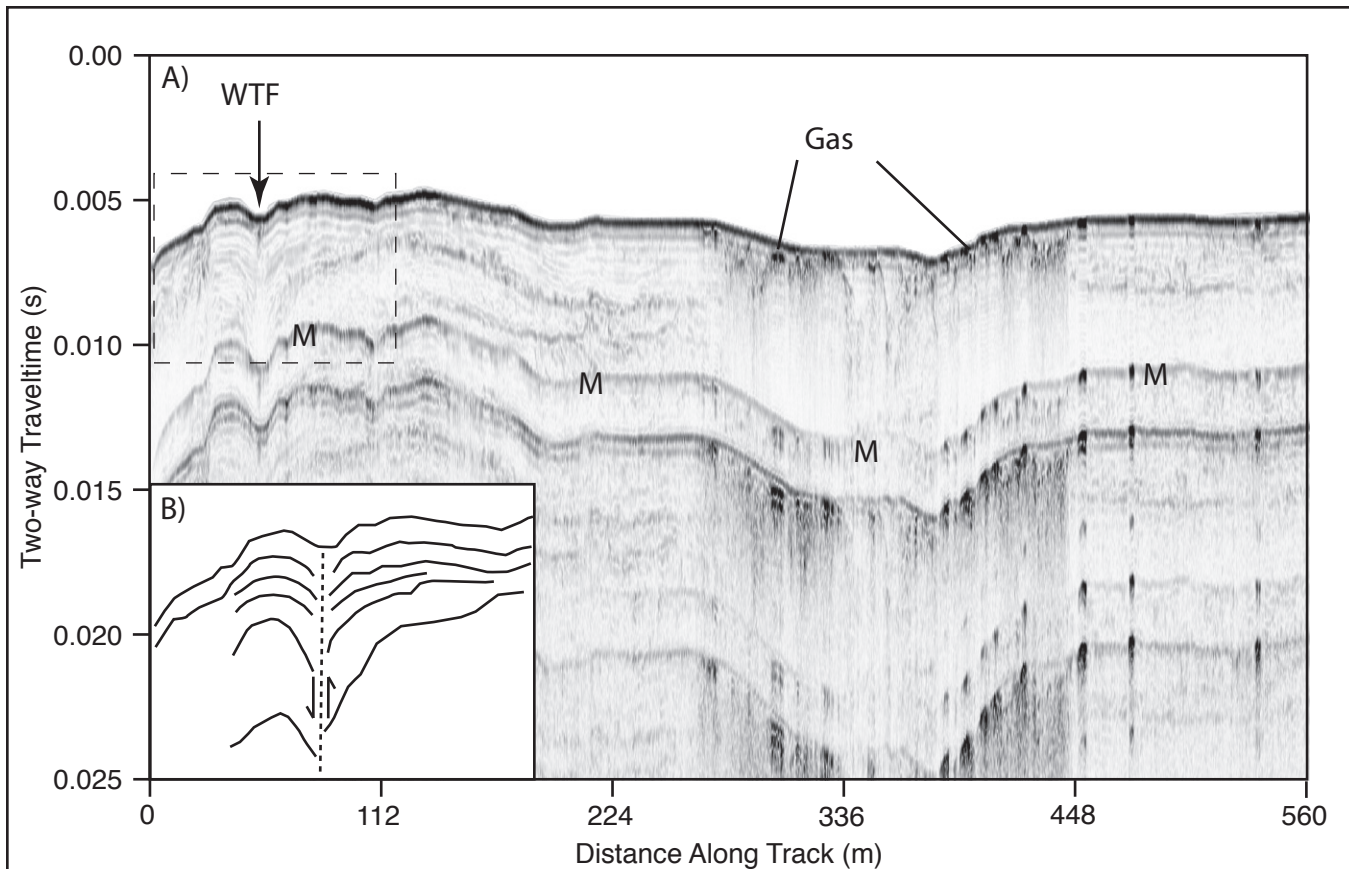


Figure 7. CHIRP profile near Baldwin Beach showing offshore trace of the West Tahoe fault (plotted E-W). Inset: Line diagram showing relative offset of sedimentary layers.

reflector at ~ 3 m depth, most likely representing both sand layers as they are too close to resolve. The distinct acoustic horizon representing the Tsoyowata Ash can be traced basin wide and occurs at a depth of ~ 7.6 m on the fault (D3Line08 Lline), providing a corresponding sedimentation rate of ~ 1 mm/yr over the last 8 ka. The averaged sedimentation rate in FLL during the last 5 ka is similar to that of Emerald Bay where a ~ 4.5 m sediment core was dated near the bottom at $\sim 4,000$ yr B.P.

Two mid-lake profiles image a second fault that has the same MRE horizon as the WTF. The mid-lake fault clearly offsets the lacustrine sediments up to 1.5 m vertically, but the along strike nature to the north is poorly constrained.

Baldwin Beach

CHIRP profiles and radiocarbon analysis of a submerged tree on the down thrown hanging wall block, offshore Baldwin Beach, may help constrain the location and timing of the MRE along the WTF. Profiles along the shallow sandy shelf do show faulted sediments (Figures 6 & 7), suggesting the fault steps onshore in this vicinity. A submerged rooted tree offshore Baldwin Beach at a water depth of ~ 4 m was radiocarbon dated at 4.6 ka. The timing of the submersion is consistent with the fault activity observed in FLL.

Onshore scarp mapping

The precise location of the WTF as it extends into Lake Tahoe is difficult to determine, but CHIRP imagery preclude it from extending through Emerald Bay (Dingler et al., 2007) and profiles in Lake Tahoe require it to be west of Baldwin Beach. A conspicuous (~ 10 m) scarp at the western edge of Baldwin Beach, containing rounded pebbles and gravel along the relatively flat top, is a possible candidate for an uplifted lake terrace. However, this feature doesn't require tectonic uplift and may have formed during a Pleistocene high-shoreline. Additionally, potential pockmarks in the bathymetry (Dingler et al., 2007), along the base of the lake wall, offshore of the entrance to Emerald Bay, follow the predicted trend of the fault.

Field reconnaissance south of HW89 revealed a ~1 km long, down-to-the-east fault scarp with varying height depending on the age of the offset material. Scarps through what appear to be Pleistocene alluvial slopes (McCarthy, 2005) are 10-15 m high, where younger, most likely post-Tioga scarps are 3-4 m high. The scarp trends north-south and aligns with the overall trend of the southern segment of the WTF. Scarp degradation and a relaxed slope suggest significant time lapse since the MRE.

Conclusions

The MRE along the Fallen Leaf segment of the WTF occurred ~4-5 ka. Lacustrine sediments are vertically offset by ~ 3 m, producing a moment magnitude $M_w=7.1$ (Hanks and Kanamori, 1979) (assuming the entire 45 km-long WTF ruptured to a depth of 13 km), a magnitude similar to other major dip-slip events in the Basin and Range, and on the nearby Genoa Fault (Wells and Coppersmith, 1994, Ramelli et al., 1999). Assuming all lake sediments were deposited post-Tioga, this assumption allows an estimate for the slip-rate using the total offset (~9 m) across the dipping sediments adjacent to the fault in the southern basin. Vertical slip-rate estimate for the Fallen Leaf segment varies between 0.6-0.8 mm/yr, depending on the interpretation of earlier Holocene events, but is a similar rate to estimates along the central portion of the fault. Based on fault length, slip-per-event estimates, and geomorphic expression, the WTF appears most similar to the nearby Genoa Fault, with a potential to generate $M \geq 7.0$ earthquakes.

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